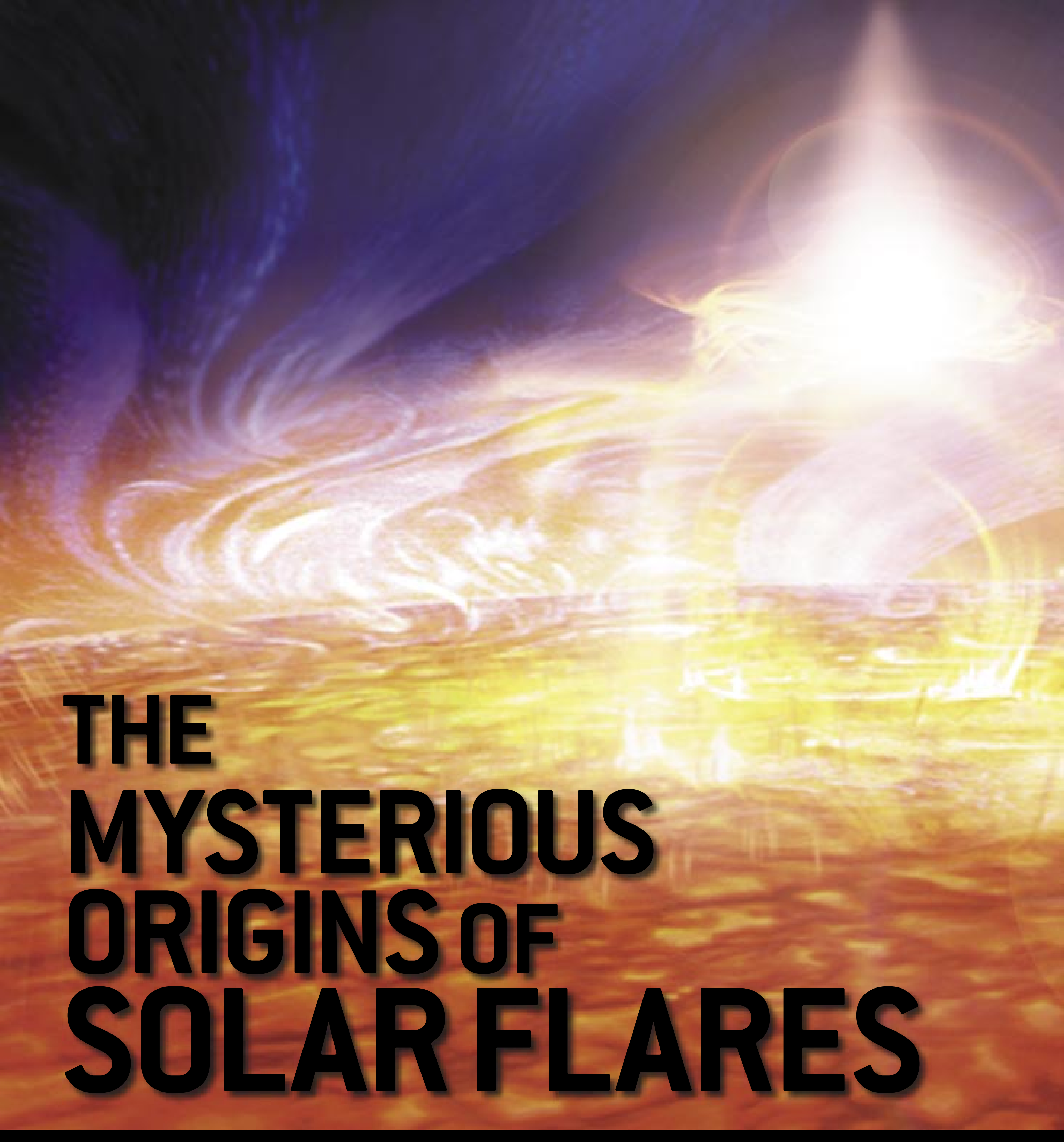
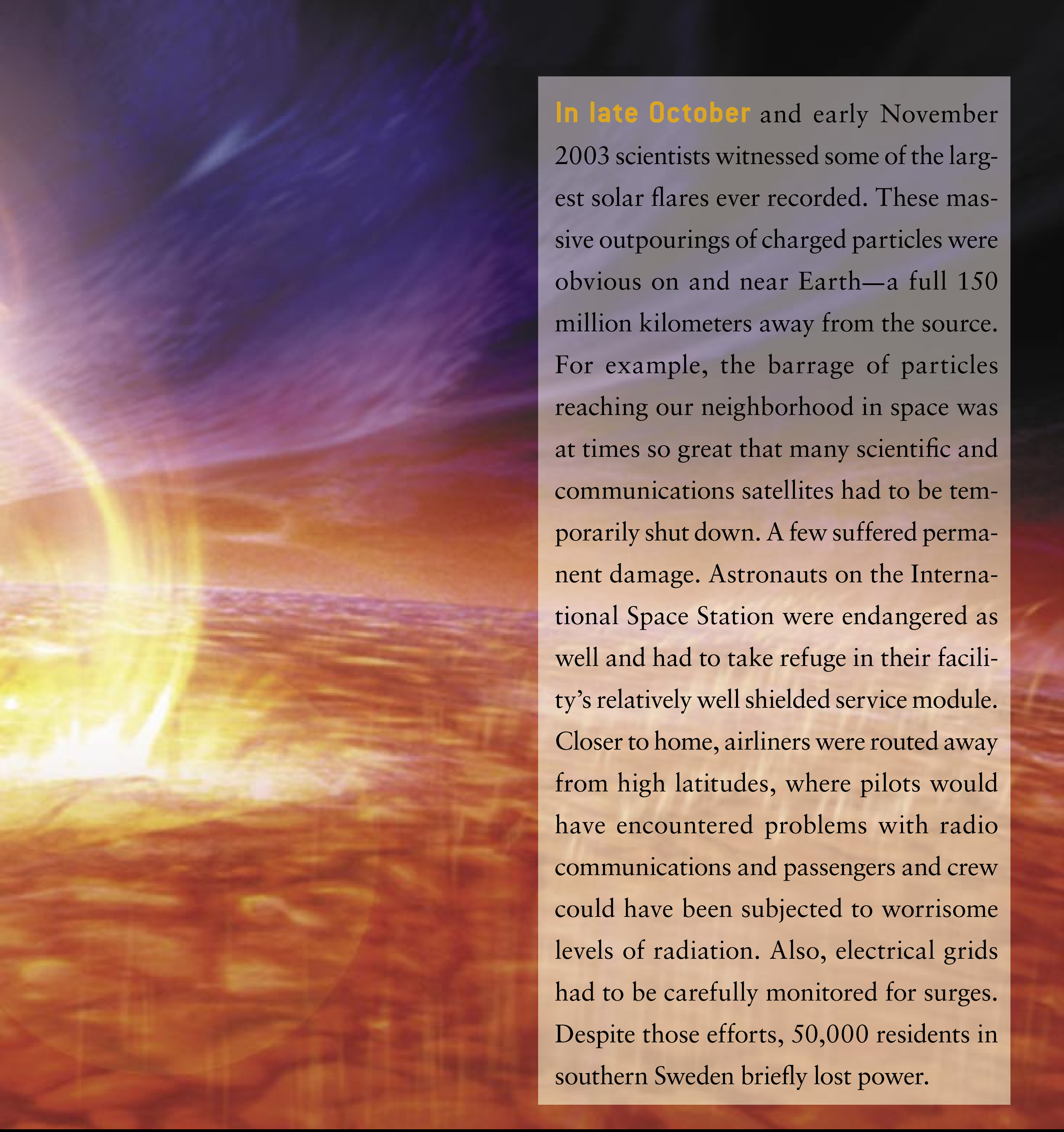


THE MYSTERIOUS ORIGINS OF SOLAR FLARES

New observations are beginning to reveal what triggers these huge explosions of the sun’s atmosphere

By Gordon D. Holman

In late October and early November 2003 scientists witnessed some of the largest solar flares ever recorded. These massive outpourings of charged particles were obvious on and near Earth—a full 150 million kilometers away from the source. For example, the barrage of particles reaching our neighborhood in space was at times so great that many scientific and communications satellites had to be temporarily shut down. A few suffered permanent damage. Astronauts on the International Space Station were endangered as well and had to take refuge in their facility's relatively well shielded service module. Closer to home, airliners were routed away from high latitudes, where pilots would have encountered problems with radio communications and passengers and crew could have been subjected to worrisome levels of radiation. Also, electrical grids had to be carefully monitored for surges. Despite those efforts, 50,000 residents in southern Sweden briefly lost power.



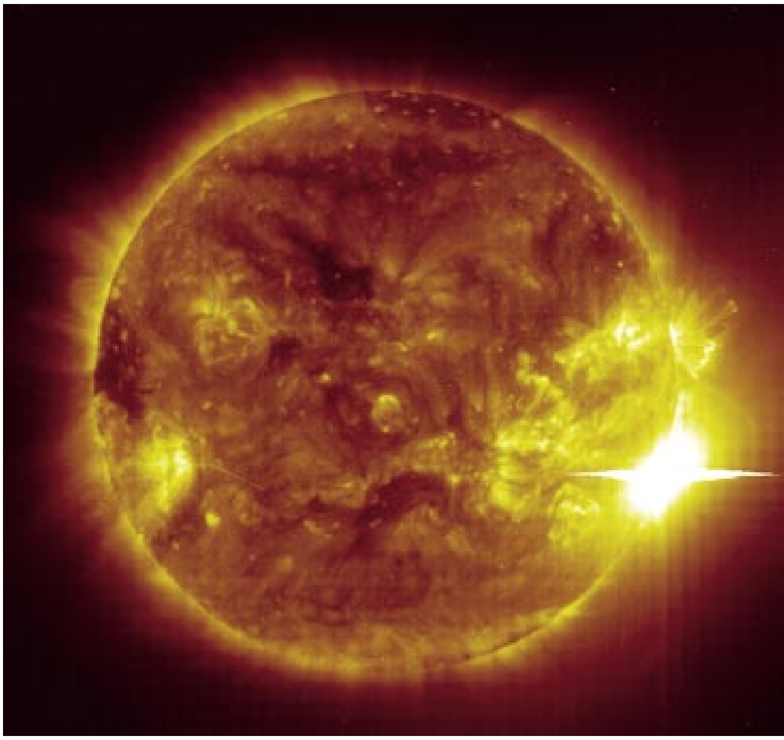
SUDDEN EXPLOSIONS of the solar atmosphere release the energy equivalent of billions of atomic bombs within the span of just a few minutes. The cause is an abrupt rearrangement of solar magnetic fields, which arch upward from the surface of the sun and can be traced by the glowing gas they hold.

Fortunately, Earth's magnetic field and atmosphere protect the overwhelming majority of people from the ravages of even the worst solar storms. But society's increasing reliance on technology makes nearly everyone vulnerable to some extent [see "The Fury of Space Storms," by James L. Burch; SCIENTIFIC AMERICAN, April 2001]. The greatest potential for damage during a large flare comes from material shot rapidly off the sun's outer atmosphere—coronal mass ejections, in space physicist lingo. Some of these events send huge quantities of ionized gas on a collision course with Earth, as was the case for more than one of the exceptionally large flares that occurred in 2003.

Although scientists have long sought to figure out what drives both flares and the coronal mass ejections that accompany many of them, only in the past decade or so have observations been good enough to reveal their intricacies and to elucidate the physical mechanism behind them, thanks to new technologies introduced during the 1990s. The key turns out to be a sudden rearrangement of magnetic field lines, a phenomenon called reconnection.

Fair and Mild, Highs of Two Million

THE WEATHER ON EARTH, complicated as it is, at least results from familiar processes: solar heating, differences in air pressure and shifting wind patterns. So most people have an intuitive grasp of why, for instance, the skies can be sunny one day and rainy the next. In contrast, solar flares and other aspects of "space weather" involve the interplay of magnetic fields and gas that is hot enough to become ionized (which is to say that the constituent atoms are stripped of their electrons). Such interactions cannot be seen directly and can be tricky to visualize, even for specialists. The leading idea for how these goings-on generate solar flares—magnetic reconnection—dates back to the 1950s and 1960s. Yet observational evidence for it has been slow in coming, so much so that some space physicists were beginning to have their doubts about the theory's merit.



RECORD-BREAKING FLARE erupted near the edge of the sun on November 4, 2003. The flash of radiation overwhelmed the detector on the Solar and Heliospheric Observatory's extreme-ultraviolet telescope, leaving a spurious horizontal line on this image (*left*). As with other such events, a sunspot—the site of particularly intense magnetic fields—was situated nearby (*right*).

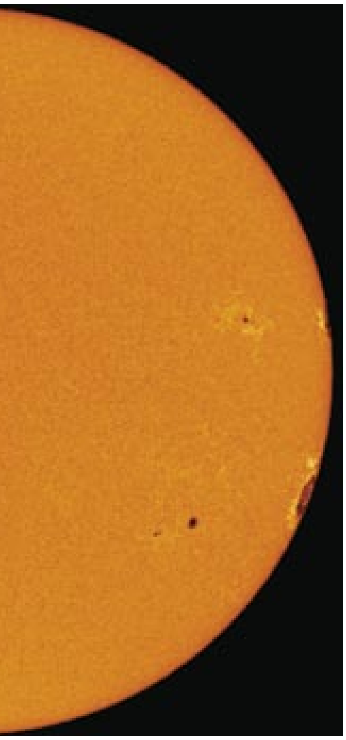
DON DIXON (*preceding pages*); SOHO/EIT (ESA AND NASA) (*flare and sunspot*) (*above*)

Overview/*Physics of Flares*

- Solar flares can release the energy equivalent of billions of atomic bombs in the span of just a few minutes. These explosions give off a burst of x-rays and charged particles, some of which may later hit Earth, endangering satellites and causing power outages.
- The sun's tumultuous magnetic fields provide the fuel of flares. The sudden release of energy in a flare results from a process called reconnection, whereby oppositely directed magnetic field lines come together and partially annihilate each other.
- Although theoretical studies of magnetic reconnection on the sun have been carried out for decades, only recently have space probes uncovered observational evidence for this phenomenon. The telltale signs include pointed magnetic loops located below the spot where magnetic reconnection is taking place.

Scientists generally agree that the energy released in a flare must first be stored in the sun's magnetic fields. That surmise follows from the fact that flares erupt from parts of the sun called active regions, where solar magnetic fields are much stronger than average. These areas are most easily identified by the presence of sunspots—those dark-looking patches host the most intense magnetic fields on the sun. In these zones, the lines of force of the magnetic field extend from the surface into the corona, the outer layer of the solar atmosphere, arching upward in broad loops, which trap hot gas—and I do mean *hot:* several million kelvins. These temperatures are high enough to cause the contained gas to emit both extreme ultraviolet radiation and x-rays [see "The Paradox of the Sun's Hot Corona," by Bhola N. Dwivedi and Kenneth J. H. Phillips; SCIENTIFIC AMERICAN, June 2001]. The flares that occasionally burst forth from active regions emanate from such magnetic features, causing the gas in the loops to heat up more than usual—typically to between 10 million and 40 million kelvins.

Beyond the general association between flares and strong magnetic fields, the picture of how things work has long remained very fuzzy. For example, it has dawned only gradually on astronomers that the magnetic field loops and hot gas involved in flares may differ quite a bit from very similar-looking structures found elsewhere within active regions. The



first signs of that distinction came nearly 14 years ago, from measurements carried out by the Japanese Yohkoh satellite, the first space probe to obtain pictures of solar flares at wavelengths that extend up to moderately high x-ray energies (making them useful in picking out very hot gas). For some of these events, the tops of the magnetic loops showed a curious cusp, giving them the pointed appearance of a Gothic arch, rather than presenting the usual rounded peak.

While examining the Yohkoh images, Satoshi Masuda, then a graduate student at the University of Tokyo, discovered that the cusp region of one 1992 flare emitted an unusually large dollop of relatively high energy (short-wavelength) x-rays. He concluded that the source was a pocket of exceptionally hot gas (about 100 million kelvins), which would be expected to glow brightly at short x-ray wavelengths. Alternatively, something could have accelerated electrons in this region to extremely high velocities, causing them to emit x-rays when they ran into ions in the surrounding gas and suddenly slowed down.

Either one of these possibilities was puzzling. If the gas was that scorching, how could it stay confined to such a small spot? And if instead the x-rays came from accelerated electrons bashing into ions, why was the radiation coming from a compact source near the top of the loop and not just from the bottom, where the density of gas is highest?

To solve these riddles, space physicists required measurements that could distinguish the effects of hot gas from those of accelerated electrons. And to understand when and where relevant activity was taking place, they needed frequent images of solar radiation in the full range of x-ray and gamma-ray energies. The lack of such information handicapped investigators for most of the next decade, but in 2002 NASA launched the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), which has now captured detailed views of the cusp region in certain solar flares. In doing so, RHESSI has provided persuasive evidence—essentially a smoking gun—confirming that magnetic reconnection is responsible for both flares and coronal mass ejections.

Crossing the Lines

FOLLOWING WHAT EXACTLY HAPPENS during a reconnection event requires, first off, a general understanding of how invisible magnetic loops can trap hot gas in the solar atmosphere. Such gas is better termed plasma, because it consists mostly of electrons and protons separated from one another, which means that it is electrically conductive. An electric field can thus push these charge-carrying particles along it, creating electric currents. A magnetic field exerts forces on such charged particles, too, sending them twirling around magnetic field lines.

Although electrons and protons are constrained to circle magnetic field lines in this manner, they can move relatively freely along the length of those lines. I say “relatively” because charged particles will experience a retarding force if they travel along magnetic field lines that converge. So, for example, during its descent from the top of a loop toward the bottom, a particle will be slowed as it approaches one of the so-called foot points of the loop, where the field lines converge and the magnetic field is more intense. Eventually the increasingly strong field brings the electron or proton to a halt and then pushes it back up. This process is akin to throwing a cannonball against a mattress. Unlike the ball, however, which temporarily gives up its energy of motion to compress the mattress springs, charged particles on the sun do not transfer energy to the magnetic field. Rather the energy of their downward travel shifts to increase the frequency of their circular motion around magnetic field lines. In this way, the two foot points of a magnetic loop act like mirrors, reflecting protons and electrons back and forth in what is essentially a big trap for charged particles.

Surprisingly enough, the plasma itself can affect the magnetic field lines holding it. It does so because being a sea of charged particles, it can contain electric currents, which arise whenever there is a voltage difference present to drive them. In more familiar electric circuits—say, the one found in a flashlight—a battery provides the driving voltage. On the sun, nothing like a battery exists, but the shifting magnetic fields induce voltage differences (according to the same physical principles that operate an electric generator), thereby giving rise to electric currents. Making matters even more complicated, these currents produce new magnetic fields. This effect, combined with the tendency for magnetic foot points to move around erratically, results in an ever changing panoply of highly distorted

INTENSE AURORAL DISPLAY lit up the night sky over Alaska in October 2003 as a result of heightened solar activity. Outpourings of charged particles from the sun can spawn an aurora when they reach Earth and impinge on the upper atmosphere. These and other energetic particles travel downward along lines of force of the magnetic field.

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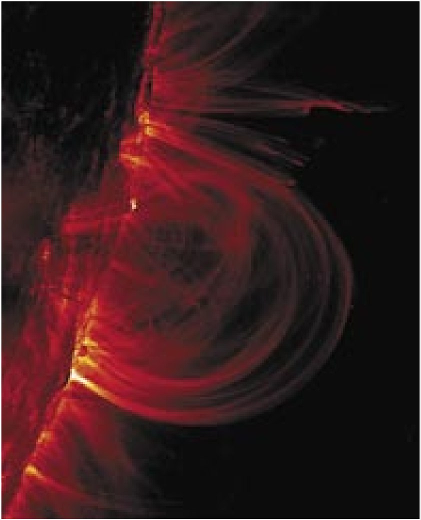
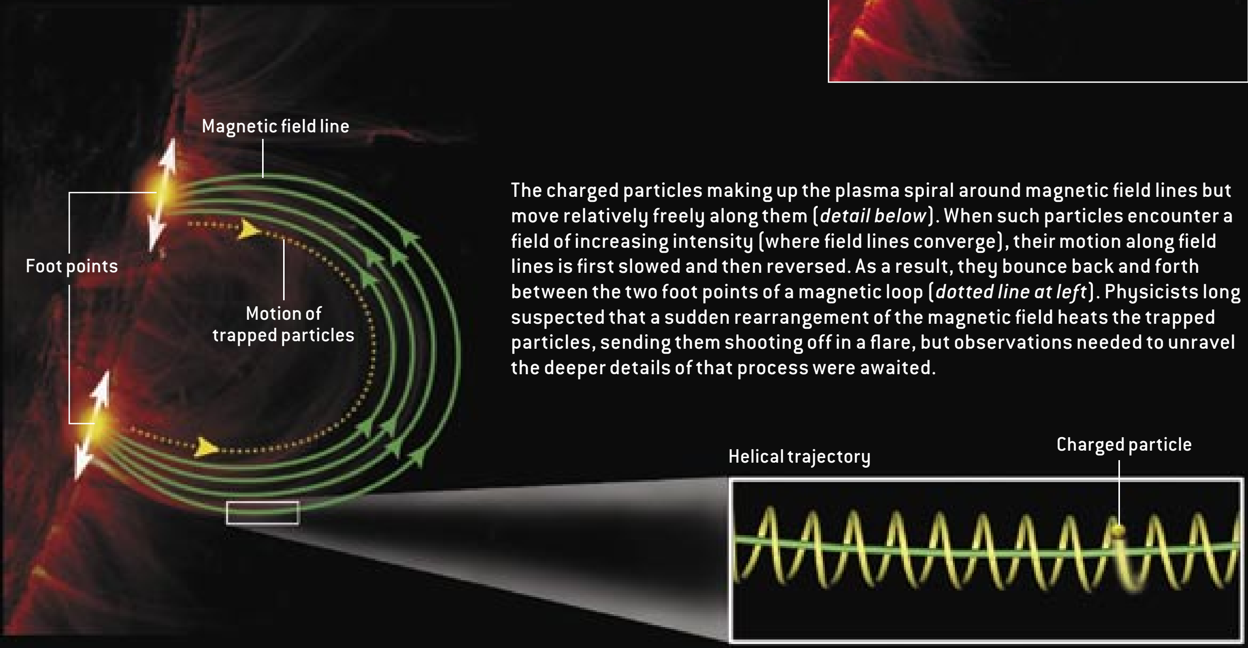
FLARE FODDER

Shifting magnetic fields and searingly hot plasma—gas in which the constituent atoms are stripped of their electrons—provide all the ingredients needed for a flare (*below*), although the recipe for how they come together to produce a flare has only recently been deciphered [*see box on page 44*].



Glowing loops of gas commonly jut from the solar surface, as seen in this extreme-ultraviolet image from the Transition Region and Coronal Explorer (TRACE) space probe. The luminous lines follow the local magnetic field, which changes over time as motion of the hot plasma near and just underneath the visible surface of the sun shifts the "foot points," the places where the field lines are anchored.



The charged particles making up the plasma spiral around magnetic field lines but move relatively freely along them (*detail below*). When such particles encounter a field of increasing intensity (where field lines converge), their motion along field lines is first slowed and then reversed. As a result, they bounce back and forth between the two foot points of a magnetic loop (*dotted line at left*). Physicists long suspected that a sudden rearrangement of the magnetic field heats the trapped particles, sending them shooting off in a flare, but observations needed to unravel the deeper details of that process were awaited.

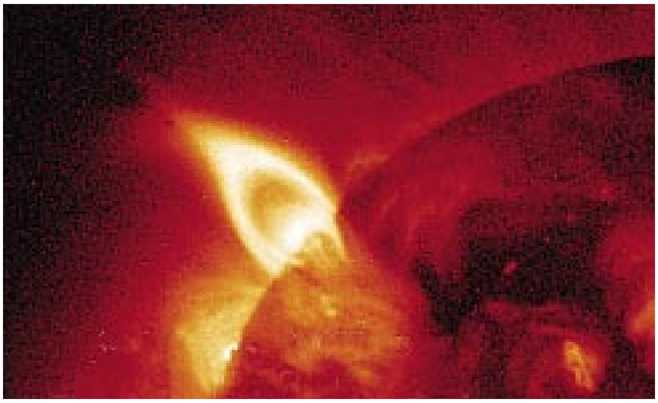
TRACE (STANFORD-LOCKHEED INSTITUTE FOR SPACE RESEARCH/NASA SMALL EXPLORER PROGRAM) (*image*); DON DIXON (*illustration*)

magnetic fields in the solar atmosphere, ones that contain considerable magnetic field energy—the fuel of solar flares.

This part of the story describes just some of the basic physics at work, which scientists have understood for many decades. The problem arises when one tries to explain exactly how all this magnetic field energy is converted into heat, accelerated particles and ejected material. One possibility comes simply from a consideration of any electric circuit, which is characterized not just by the current it carries and the voltage driving the flow of charge but also by the electrical resistance present. The filament in a lightbulb, for example, offers resistance to the electric current flowing through it, dissipating electrical energy by turning it into light and heat. The solar atmosphere offers electrical resistance because the charged particles making up the electric currents sometimes collide with one another, impeding their motion and warming things up. Also, the voltage that drives the current has an electric field associated with it. If this electric field is strong enough, electrons and ions will be accelerated out of the hot plasma. Voilà: heating and high-energy particles, the components of a flare.

This neat explanation, alas, does not hold up very well under scrutiny. One reason is that the electrical resistance in the corona is typically quite low—too low to account for the explosive rate at which solar flares brighten. And even if the resistance were higher, explaining how the required amount of magnetic energy could be concentrated in one place and released in a sudden burst would still be difficult. Investigators concluded decades ago that the generation of a voltage driving a simple, single current could not heat the solar atmosphere quickly enough or produce a flux of accelerated particles that is sufficient to make a flare.

Over the years, space physicists have come up with various



POST-FLARE LOOPS sometimes show a distinct cusp at the top. This geometry of the glowing gas reflects a pinching of the local magnetic field. Such pinching can bring about the magnetic reconnection needed to power flares and sometimes remains in evidence for days afterward.

YOHKOH (LOCKHEED MARTIN SOLAR AND ASTROPHYSICS LABORATORY/NATIONAL ASTRONOMICAL OBSERVATORY OF JAPAN/UNIVERSITY OF TOKYO/NASA/ISAS)

ideas of greater complexity: perhaps, they reasoned, flares result from many different currents coming together or from a volume of turbulent plasma waves and the random electric fields associated with them. Such special arrangements are probably capable of bringing about a flare, but these mechanisms cannot account for all the observations, especially the tendency for coronal mass ejections to accompany large flares. A more promising theory involves the dynamics not just of the electric field but also of its magnetic counterpart. So let me describe the physics of such fields in greater detail.

Magnetic fields have a direction associated with them. Around a bar magnet, for example, the lines of force point from the north pole to the south. If two parallel but oppositely directed magnetic fields are brought together in plasma, an electric current will form between them, taking the shape of a flat sheet. (Most people are used to thinking of current as flowing one-dimensionally—say, along a wire—but on the sun, where the entire atmosphere is conductive, nothing prevents it from flowing in two-dimensional sheets.) The energy contained in these oppositely directed magnetic fields would then decrease over time as resistance dissipated the electric current in the sheet.

In 1956 the late Peter Alan Sweet, who was then working at the University of London Observatory, realized that the energy in the magnetic field would decline much faster if the oppositely directed field lines actually broke apart and then rejoined, or reconnected, in the current sheet that formed between them. As a result, the two opposing fields would cancel each other in a burst of energy, almost like the annihilation of matter and antimatter. Adjacent magnetic fields and the plasma in which they were embedded could then flow into the sheet from both sides. The physics of this phenomenon is such that newly created magnetic fields, ones connecting the formerly separated lines of force, and plasma would be ejected out the ends of the sheet. In the late 1950s and early 1960s Eugene N. Parker of the University of Chicago worked out the mathematics describing this process, now called Sweet-Parker magnetic reconnection.

But such reconnection cannot be the full explanation of what goes on during a flare, because the rearrangement of magnetic field lines takes place too slowly to account for the dazzling rate of energy release. Realizing this shortcoming of the new model, in 1963 the late Harry E. Petschek of Avco-Everett Research Laboratory in Everett, Mass., turned his attention to the problem and determined that under certain circumstances reconnection takes place much faster than the Sweet-Parker rate. The phenomenon he analyzed is now referred to as Petschek or fast reconnection, in contrast to what Sweet and Parker first described, called slow reconnection.

Seeing Is Believing

IN BOTH FAST AND SLOW RECONNECTION, the thickness of the current sheet is tiny—just meters, which is too small for today's generation of instruments to resolve when observing the sun. Still, both processes give rise to an important phenomenon that can be detected: the creation of magnetic fields in distinct regions. Have the images from modern space probes revealed such telltale features? Perhaps.

Although reconnection might well be ubiquitous on the sun, finding direct evidence for it has proved difficult. The RHESSI mission helped enormously in this regard. In 2003 Linhui Sui, then a graduate student from the Catholic University of America working with me at the NASA Goddard Space Flight Center, was analyzing RHESSI observations of a flare of moderate intensity that occurred on April 15, 2002. This event was of special interest because it gave off a coronal mass ejection at an angle that made it easy to view. Moreover, the flare had a simple loop structure. So for the most part, it appeared very normal. Sui noticed, however, a compact source of weak x-rays hovering above the magnetic loop, seemingly unconnected to it. Intrigued but uncertain of the reality of this detached source, we obtained a series of images from the beginning to the end of the flare, a sequence that covered about 10 minutes.

It was real all right. Early on, the enigmatic x-ray source sat near the top of the loop. As the flare began to give off higher-energy x-rays, the top of the loop moved downward, while the compact source remained stationary. At the climax of the flare, when the higher-energy x-rays reached their peak intensity, the loop abruptly changed direction and started upward. The mysterious source of x-rays began to shift upward as well, but it was going much faster. Within two minutes, this x-ray source faded and disappeared. No one had ever seen such

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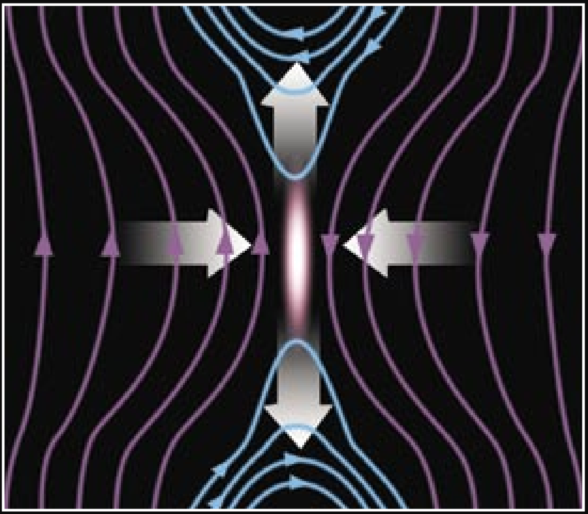
MAKING CONNECTIONS

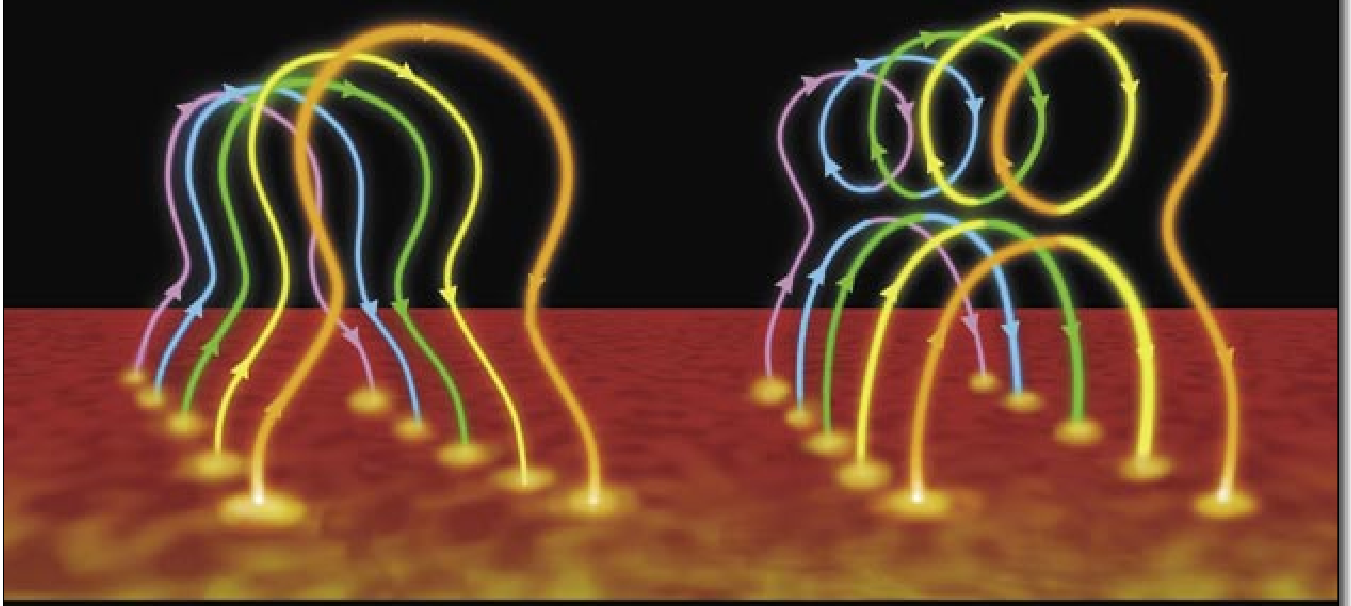
The energy source for solar flares is a phenomenon called magnetic reconnection, in which the sun's magnetic field lines join and quickly reconfigure themselves. Such reconnection events draw energy from the magnetic field, using it to heat the sun's atmosphere locally and to accelerate charged particles to high speeds.

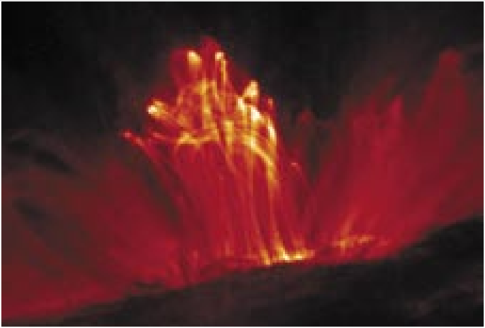
REWIRING THE FIELD

In general, magnetic reconnection occurs when oppositely directed magnetic field lines are brought together. In the diagram at the right, up- and down-pointing field lines (*purple*) move toward the center. A vertically oriented sheet of electric current (*pink, seen here on edge*) then forms. Oppositely directed magnetic fields can merge within this current sheet, partially annihilating each other and releasing the magnetic energy they contain. New field lines (*blue*) form above and below the current sheet and move rapidly away from the site of reconnection.



On the sun (*below*), such reconnection events can get exceedingly complicated. There they sometimes reconfigure solar arcades, the series of arching field lines that often occur back to back. For example, a set of such lines can sometimes all pinch inward simultaneously (*below left*). If the process continues, it can result in wholesale reconnection, sparking a flare and leaving a helical magnetic field above a low arcade of loops below (*below right, spots where different colors meet mark where reconnection occurred*). The helical field and the material it contains may expand outward, becoming a coronal mass ejection.

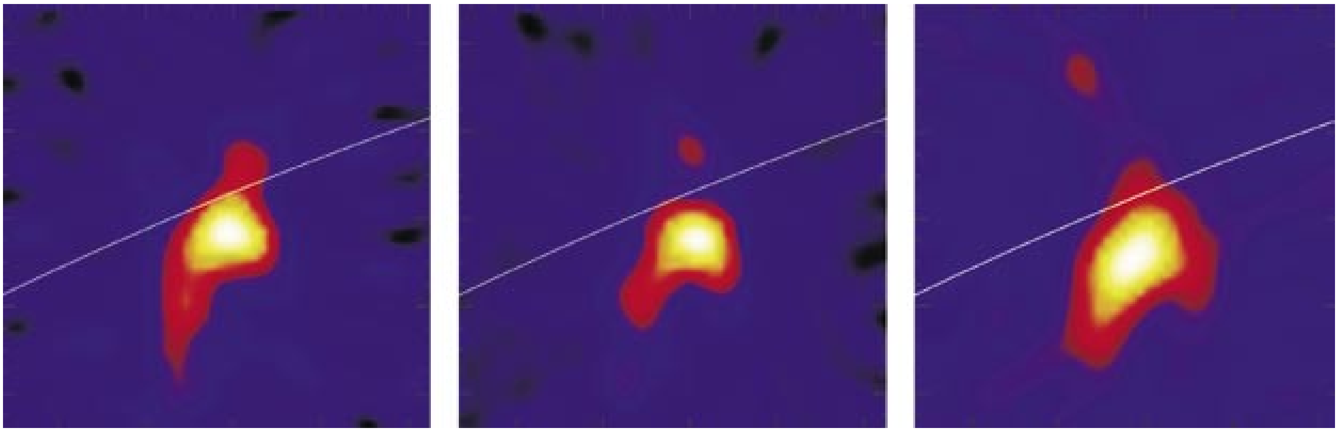




LINGERING EVIDENCE

Such reconnection events often leave telltale signs. The image at the left, obtained with the TRACE probe in September 2000, shows a tangled web of loops that were evident two hours after a solar flare took place in this locale. Although the configuration of the magnetic field before this flare occurred is unknown, the jumbled appearance of the loops in this image suggests that significant magnetic reconnection must have taken place, perhaps leaving parts of the magnetic field largely disconnected from the solar surface.

DON DIXON (*illustrations*); TRACE (*image*)



X-RAY SNAPSHOTS that were obtained by the Ramaty High Energy Solar Spectroscopic Imager depict the flare of April 15, 2002, which was accompanied by a coronal mass ejection. During this flare, a source of x-rays appears as a red bulge just above the main loop of hot gas (*left*) and above the visible edge of the sun (*white line*). This source remains stationary for some minutes as the top of the loop descends (*center*) but later shoots off rapidly into space (*right*). The sequence supports the idea that reconnection at the top of magnetic loops accounts for flares and coronal mass ejections, because the pattern is exactly what one would expect if the magnetic field were reconnecting above the loop, allowing half of the newly formed field lines to shift downward while the other half raced upward, powering a coronal mass ejection.

events unfold before. The x-ray source that at first seemed motionless ended up shooting outward from the sun at 300 kilometers a second—the speed at which the coronal mass ejection that accompanied this flare blasted off. Sui and I suspected that we had at last discovered the elusive origins of such explosive releases of material. Even better, measurements of the temperature pinpointed where the energy was coming from: between the top of the magnetic loop and the curiously behaving source of x-rays.

This pattern matches what one would expect to see if the magnetic field were reconnecting above the loop in a vertically oriented sheet of electric current. Coronal magnetic field and plasma presumably flowed horizontally into the current sheet from both sides. The oppositely directed magnetic fields reconnected there, and half of the newly formed field lines shifted rapidly downward, where they stacked up on existing magnetic loops. The other half of the reconnected magnetic field raced upward, building up a large, twisted magnetic loop, parts of which were unconnected to the sun. At least in some flares, these twisted magnetic field loops must become coronal mass ejections. Magnetic reconnection provides a way for the central part of such a loop (and the bubble of plasma in which it resides) to escape the sun—as if the tethers holding down a balloon were suddenly cut.

The picture that emerged from our study of this 2002 event also helps to elucidate the earlier Yohkoh observations. The cusp seen at the top of the 1992 flare loops must have sat just below an invisible current sheet, where newly reconnected magnetic field lines were continuously forming and collapsing onto the field below. The cusp shone brightly at x-ray wavelengths because of the constant injection of heated plasma and accelerated electrons from the current sheet above and, possibly, because of heating and electron acceleration in the cusp itself.

An explanation of how at least some solar flares and coronal mass ejections form now appears at hand, but many questions remain to be answered. For example: What is responsible for particle acceleration in flares? And what causes the sudden onset of magnetic reconnection? Space physicists hope to find answers to these questions soon as we continue to study flares using RHESSI and other solar observatories, including the soon-to-be-launched Solar B and STEREO probes. The Solar B mission will map solar magnetic fields in great detail. The STEREO mission (shorthand for *S*olar *TE*rrestrial *RE*lations *O*bservatory) will place two spacecraft into positions from which three-dimensional stereo image pairs of the sun can be obtained. Investigators hope that these views will provide more clues to the geometry of coronal mass ejections as they leave the sun and travel through interplanetary space.

Scientists' ability to anticipate violent space weather will no doubt improve in coming years. Gains will come from both a greater understanding of the mechanisms driving solar flares and the increasingly sophisticated tools available to monitor space around the sun and around Earth. Those of us studying space storms thus expect that many of our lingering mysteries may soon be solved. We look forward to the time when our forecasts of space weather become as commonplace as the predictions meteorologists routinely provide.

MORE TO EXPLORE

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Multiwavelength Analysis of a Solar Flare on 2002 April 15. Linhui Sui, Gordon D. Holman, Stephen M. White and Jie Zhang in *Astrophysical Journal,* Vol. 633, pages 1175–1186; November 10, 2005.

General information about solar flares can be found at **http://hesperia.gsfc.nasa.gov/sftheory/**

Information about the Ramaty High Energy Solar Spectroscopic Imager can be found at **http://hesperia.gsfc.nasa.gov/hessi/**

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